Reinventing Crew Scheduling At Netherlands Railways

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Reinventing Crew Scheduling at Netherlands Railways

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Abstract

In this paper we describe the successful application of a sophisticated Operations Research model and the corresponding solution techniques for scheduling the 6,500+ drivers and conductors of the Dutch railway operator NS Reizigers (Netherlands Railways). In 2001 the drivers and conductors were very dissatisfied with the structure of their duties, which led to nation wide strikes. However, the application of the model described in this paper led to the development of an alternative production model ('Sharing Sweet&Sour') that both satisfied the drivers and conductors, and at the same time supported an increment of the punctuality and efficiency of the railway services. The plans produced according to the alternative production model trimmed personnel costs by about \$4.8 million (or 1.2%) per year. Moreover, it was shown that cost reductions of over \$7 million per year are also achievable.

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1 Introduction

NS Reizigers (Netherlands Railways) is the main Dutch railway operator of passenger trains, employing 3,000+ drivers and 3,500+ conductors in 29 crew depots. Each workday, about 5,000 timetabled trains are operated. For a railway operator, crew scheduling is a fundamental task. Until the year 2000, the crew scheduling process of NS Reizigers was carried out mainly manually, although several supporting information systems were used. However, these systems were not able to provide real *active* support in the crew scheduling process by automatically generating duties for drivers and conductors. The crew scheduling process relied heavily on the experience and the craftsmanship of the planners. Since 2000, NS Reizigers has been using the crew scheduling system TURNI that *does* provide active support in the crew scheduling process. TURNI was developed by Double-Click sas [6] and was customized several times to cope with the complex rules that are to be satisfied by the crew schedules of NS Reizigers.

In 2001, a conflict related to the structure of the duties of the drivers and conductors arose between the drivers and conductors themselves, the unions, and the management of NS Reizigers. This conflict seemed to be unsolvable and paralyzed the railway system. However, in this paper we describe how TURNI was used to support the development of the new production model 'Sharing Sweet&Sour' (in Dutch: 'Lusten&Lasten Delen'). This model was acceptable for all parties, by increasing both the quality of the work of the drivers and conductors as well as the punctuality and efficiency of the railway system. Here a production model is a set of rules that has to be applied in the generation of the duties for drivers and conductors. The kernel of the alternative production model consists of a set of rules that are so complex that it is nearly impossible to take them into account efficiently when planning manually. Therefore, automated support is indispensable. Besides that, the plans produced according to the alternative production model trimmed personnel costs by several millions of dollars per year, as was demonstrated by the crew schedules for 2004.

This paper is structured as follows. In Section 2, we describe the reason for the search for the alternative production model. Section 3 describes the process of the development of the alternative production model. In Section 4 we describe some characteristics of this model. Section 5 focuses on the planning support system TURNI, its underlying set covering model, and the involved solution techniques. In Section 6 we describe the efficiency improvement that has been accomplished, and in Section 7 we end with some conclusions.

2 Foreplay

On June 10, 2001, the production model of the by then infamous so-called 'Church Circles' (in Dutch: 'Rondjes om de Kerk') was introduced at NS Reizigers. This production model was mainly inspired by the aim of the management to improve the punctuality of the railway services: according to the rules of the 'Church Circles', train drivers and conductors would operate on less different routes, and, in principle, they would transfer from one train to another only during their meal break. In this way, the usual snow-ball effect of delays of trains would be reduced. Moreover, the management also expected that this production model would lead to a better service for the passengers due to the better knowledge of the crew of local situations.

Although the unions were involved in the process towards the development of the 'Church Circles' and all obstacles seemed to be removed for the introduction on June 10, 2001, the drivers and conductors were quite unhappy when the details became apparent in the beginning of 2001. This even led to several days of strike in an attempt to prevent the introduction of this production model. These problems received much attention of the Dutch media.

After various unsuccessful mediation attempts, negotiations between the unions, the Works Council and the management led to an agreement on April 23, 2001. The agreement described a path towards normalized working relations at NS Reizigers. The signed agreement stated that the 'Church Circles' would be introduced indeed on June 10, 2001. However, at the same time, the Works Council got the opportunity to develop an alternative production model. The latter was not open-ended: if the management would not accept this alternative, then binding arbitrage should give the final decision about the production model to be operated. If the alternative production model would be accepted by the management, then it would be operated as of the 2003 timetable.

Why were the drivers and conductors so unhappy with the 'Church Circles'? The main complaint was the implied reduction in the variation of the duties. The monotony of the work was perceived as a decrease in the quality of the work. For the conductors also the increased passenger aggression and the decreased social safety played a role. These are local developments (mainly in the Randstad in the western part of the country), and according to the rules of the 'Church Circles', personnel from only a few crew depots was confronted with this passenger aggression and insafety. These crew depots considered this as an unfair division of the total amount of work. Besides these direct issues, there was also the fear that the aim of the management to introduce the 'Church Circles' was inspired by a secret agenda connected with the privatization of the unprofitable lines. Altogether, this culminated into a massive resistance among the drivers and conductors against the 'Church Circles'.

3 The development of the alternative model

The agreement of April 23, 2001, also stated that the Works Council could hire external expertise to help them in the development of the alternative production model. The Works Council finally decided to ask the combination of Basis&Beleid (a consulting company with experience with social and political conflicts) and ORTEC (a consulting company with logistic expertise) to support them. Their assignment was focused on avoiding arbitrage, since, in the end, arbitrage would lead to losers only. So, a compromise that was acceptable for all parties had to be created. However, there were many conflicting points of view. The differences between the personnel and the management were obvious, but also among the personnel there were many different opinions, depending on function, age and crew depot. Besides that, there were different points of view between the unions, and also the relation between the personnel and the Works Council was weak. Moreover, positions in the management were not stable. On the first days of 2002, the complete board of the company as well as part of the management had to leave the stage. In other words, the basis for success was not quite strong. But everybody agreed on one single issue: a solid basis for the alternative production model had to be created.

3.1 The participative approach

Logistic expertise was required and could be provided by ORTEC and by the Department of Logistics of NS Reizigers. But it was also clear that any plan developed by experts was doomed to fail. Therefore, one chose for a participative approach: the alternative production model was developed in cooperation with the personnel. The project therefore got the matching name 'You're part of it' (in Dutch: 'Je bent erbij'). Openness and transparency were the central words. The whole process could be followed via the project's own website, and the complete personnel was informed via newsletters. In the first months of the project there were discussions with 700 people from all crew depots. A list of the bottle-necks was made, and initial solutions were proposed. A book could be filled with all the mentioned bottle-necks, but the central theme in all discussions was the request for more variation in the duties.

In total 300 people were selected randomly to support the further development of the alternative production model. There were 4 groups of 75 people that came together several times in two-day working conferences. As a result, the project got alive and several alternative solutions saw the light. The working conferences gave advise to the Works Council about these alternatives. Next, the Works Council chose the alternative 'Sharing Sweet&Sour' that seemed to have the most solid basis among the drivers and conductors. After several long negotiations with the management of NS Reizigers about the final details of the alternative model, the model was also accepted by the management. This fact received again much attention in the Dutch media, since the duties of the drivers and conductors had been a hot issue for a long time already.

3.2 The role of Operations Research

But where did the alternative production model come from? Parallel to the above described qualitative process, experts from ORTEC and the Department of Logistics of NS Reizigers started to develop and to evaluate several alternatives. That was easier said than done. A timetable consists of thousands of train movements. More than 6,500 crew members have to be assigned to the corresponding tasks. Moreover, the collective labor agreements prescribe many rules that must be satisfied. For example, each crew member works on average about 8 hours per day and needs to have a meal break at an appropriate time and location. A consequence is that the crew of a train has to be exchanged regularly. The resulting connection times may not be too short. Moreover, each train driver has a license for only a limited number of rolling stock types and a limited number of routes. The resulting crew schedules had to be efficient, and the punctuality had to go up, together with the variation in the duties. Altogether, it was clear that it was an enormous challenge.

For generating duties according to many different sets of rules, the planning support system TURNI was used. This system had been used by the Department of Logistics of NS Reizigers since 2000 for generating the basic structure of the duties for drivers and conductors. By the way, TURNI was also used for generating the duties according to the rules of the 'Church Circles'. The kernel of TURNI is a set covering model that is solved by a combination of dynamic column generation, Lagrangean relaxation, and heuristic search methods. TURNI is able to generate all duties for drivers or conductors of a single workday in one single run. More details of TURNI are described in Section 5.

The computations were carried out parallel to the working conferences. The working conferences generated preferences that were translated into parameters for the model. Vice versa, the results of the model were input for the working conferences. They were also the basis for the further choices. As a result, hundreds of runs with the model were needed. Especially during the first phase of the process, many scenarios were treated in parallel by TURNI: several PC's were continuously running and solving the different scenarios.

Initially, the results were evaluated and compared with each other and with the reference scenarios (the 'Church Circles' and a green field scenario) mainly based on a small number of key performance indicators. Relevant indicators were the total number of duties (efficiency), the total number of transfers from one train to another (robustness), and the total number of routes and rolling stock types per crew depot (variation). Later the number of potential alternatives decreased, which enabled a far more in-depth evaluation of the results.

TURNI had to be updated and customized several times in order to facilitate the evaluation of the different scenarios, usually involving alternative sets of rules. In the interaction between the working conferences and the computations, the many suggestions were clustered gradually into a set of five main alternatives. On May 22, 2002, the Works Council chose for the alternative 'Sharing Sweet&Sour'. Also in the subsequent negotiations with the management of NS Reizigers, in which several parameters of the rules had to be settled, TURNI was used to evaluate the impact of the different parameter settings.

The participative approach and the development and evaluation of the different scenarios using TURNI were certainly not separate activities. Especially the *symbiosis* between the two was the basis for the success of the process. The quantitative results provided by TURNI streamlined the discussions of the working conferences. It made the discussions more objective, since the consequences of various alternatives became transparent, thereby leading to more specific discussions on the real choices to be made. The objectivity of the quantitative results also allowed the management of NS Reizigers to accept the alternative production model in the end.

4 'Sharing Sweet&Sour'

As the name of the alternative production model reveals, it aims at a fair division of the sweet and sour amounts of work among the 29 crew depots. Herewith the 'Sweet' represents the variation in the routes and the train series as well as the work on Intercity trains, and the 'Sour' mainly represents the work on lines with a lot of passenger aggression and the work on the old rolling stock. The

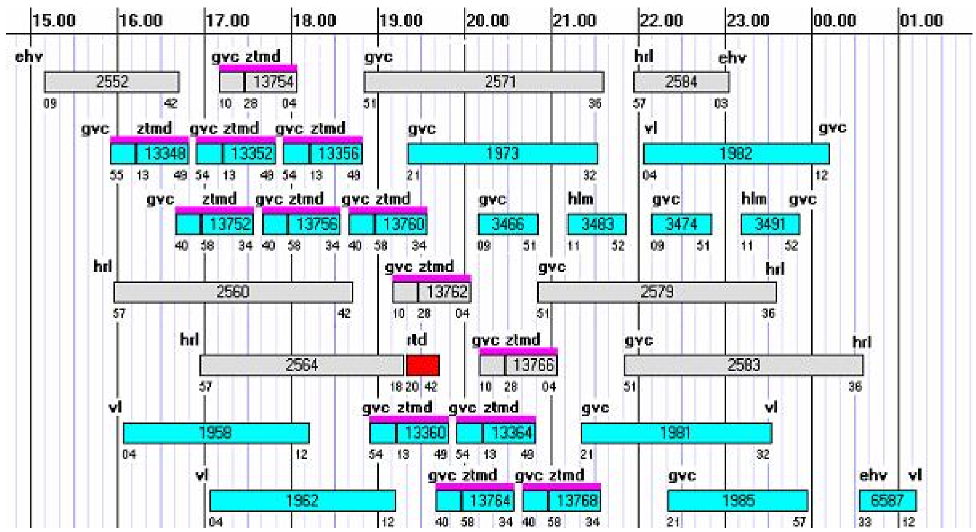

Figure 1: Seven duties for drivers from the crew depots Eindhoven (Ehv), Den Haag (Gvc), Heerlen (Hrl), and Venlo (Vl) covering part of the work on the line through Zoetermeer (Ztmd). This line bears a lot of passenger aggression.

alternative production model describes quantitative norms for the fair division of the 'Sweet&Sour' among the crew depots. For example, there is a lower bound for the number of routes per crew depot, and there is an upper bound for the percentage of work per crew depot on lines with a lot of passenger aggression. In order to represent the 'fair' division of the work, also upper bounds for the standard deviations over these percentages are defined. Altogether, the whole model is described in terms of norms that can be checked objectively.

The use of the standard deviations indicates that a 100% fair division of the 'Sweet&Sour' cannot be realized: the amount of passenger aggression in the Randstad will be higher than in the rest of the country. However, whereas in the regime of the 'Church Circles' the work on the line through Zoetermeer, which bears a lot of passenger aggression, was carried out completely by the crew depot Den Haag, in the alternative production model this work is divided among several crew depots. Crew depot Den Haag still carries out the major part of the work on the line through Zoetermeer, but the mere fact that other crew depots also contribute to the work on this line is considered to be a major leap forward in the crew depot Den Haag. Of course, the reverse of the medal is that these other crew depots are also confronted with the aggression on this line. However, this is inherent to the fair division of 'Sweet&Sour' among the crew depots. Figure 1 gives an example of a number of duties that cover part of the work on the line through Zoetermeer. Similar remarks can be made with respect to the division of the 'Sweet': in the alternative production model there may be crew depots with less 'Sweet' than in the previous production model. Thus the alternative model appeals to the solidarity among the crew depots.

The alternative production model also prescribes that the variation within the duties should be sufficiently high. In order to accomplish this, the concept Repetition-In-Duty (RID) was introduced. To that end, the railway network was divided into a number of routes, and, based on this division, the RID_d of duty d was defined as follows:

$$\mathrm{RID}_d = \frac{\#\text{ routes in duty } d}{\#\text{ different routes in duty } d}$$

The associated rule states that the overall average RID over all duties should be less than 2.7. For each crew depot the average RID should be less than 3.0. The application of such concepts as the RID, leading to complex constraints at the *depot* level (see Section 5), implies that the whole project was highly demanding from a mathematical point of view.

5 TURNI

The crew-scheduling system TURNI uses mathematical programming techniques originating from Operations Research. These techniques are based on the application of a set covering model with a number of additional constraints. The mathematical description of set covering models can be found in nearly any Operations Research textbook. In the airline industry such models have been popular for solving crew scheduling problems for many years [1, 5, 7, 12].

However, in the railway industry the sizes of the crew scheduling instances are, in general, a magnitude larger than in the airline industry, which prohibited the application of these models in the railway industry until recently. However, developments in hard- and software nowadays enable the application of such models in the railway industry as well [2, 3, 8, 9, 10, 11]. A typical instance of NS Reizigers related to the planning of a single duty type (driver or conductor) on a single workday involves about 14,000 time-tabled trips to be assigned to 1,000+ duties in 29 crew depots. This produces set covering instances with many additional nasty crew depot constraints, that are much larger than those addressed in the literature so far. Furthermore, the above figures also imply that each duty covers about 14 trips on average, which is a higher number than what is usually encountered in the airline industry.

5.1 Model description

Using the notation $t = 1, \ldots, T$ for the trips to be covered, $d = 1, \ldots, D$ for the potential duties, and $c = 1, \ldots, C$ for the additional constraints to be satisfied, the set covering model with additional constraints can be formulated as follows:

$$\min \sum_{d=1}^{D} \mathrm{cost}_d x_d \tag{1}$$

subject to

$$\sum_{d=1}^{D} a_{t,d} x_d \geq 1 \qquad \forall\ t = 1, \ldots, T \tag{2}$$

$$\sum_{d=1}^{D} b_{c,d} x_d \leq u_c \qquad \forall\ c = 1, \ldots, C \tag{3}$$

$$x_d \in \{\ 0,\ 1\} \qquad \forall\ d = 1, \ldots, D \tag{4}$$

Here the meaning of the binary decision variables is as follows:

$$x_d = \begin{cases} 1 & \text{if duty } d \text{ is selected in the final solution,} \\ 0 & \text{otherwise.} \end{cases}$$

In the 0-1 matrix $a_{t,d}$, each row represents a trip and each column represents a feasible duty, and $a_{t,d} = 1$ if and only if trip t is covered by duty d.

Besides the regular trips that *must* be covered, TURNI also allows one to include a number of *suggested* or *inadvisable* trips into the model. These trips may be covered by a duty, but they need not be covered. Adding such trips to an instance may be helpful for finding a feasible schedule or for improving the overall efficiency of the schedule. There is no constraint (2) corresponding to the inadvisable trips, which are only considered within the duty generation module. For each suggested trip t, we have a dummy duty that covers trip t only and has a cost equal to the user-defined penalty for leaving trip t uncovered.

The additional constraints (3) are not related to the individual duties (such constraints are handled at the duty generation level), but to certain forbidden combinations of duties. These are constraints at the depot level. They may be related to the alternative production model aiming at a fair division of the 'Sweet&Sour' or at appropriate values for the RID, but also to more regular issues such as the number of duties per crew depot, the percentage of night duties per depot, or the average length of the duties per crew depot.

For example, if k_d and l_d denote the crew depot and the length of duty d, respectively, and L denotes the maximum average length of the duties of each crew depot (say, 8 hours), then the following constraints guarantee that the maximum average duty length for each crew depot k is respected.

$$\sum_{d:k_d=k} (l_d - L)x_d \leq 0 \qquad \forall\ k = 1, \ldots, K \tag{5}$$

The cost coefficients cost_d in (1) represent the fact that the main objective is to minimize the number of duties required to cover all trips. However, also additional penalties for discouraging undesirable characteristics, such as an unfair division of the 'Sweet&Sour' amounts of work, P-trips[1], uncovered suggested trips, or covered inadvisable trips, are handled by these coefficients. In particular, a penalty term can be specified for each unit of slack in constraints (2), so as to reduce (or forbid) trip over-covering.

5.2 Solution method

If a set covering model is applied, then the solution mechanism usually consists of a duty generation module and a duty selection module. After a certain set

[1] P-trips are Passenger trips or Positioning trips, in which a driver or conductor is not acting as such, but is traveling as a passenger to the start of his next trip

of potential duties satisfying all the rules at the duty level has been generated, the duty selection module aims at selecting a subset of these potential duties in such a way that each of the trips is covered by at least one of the selected duties, that the additional constraints at the depot level are satisfied, and that the total involved costs are minimal. In other words, the model (1)-(4) is solved with the generated set of potential duties as input.

In more detail, the set covering model is solved in TURNI by applying dynamic column generation, Lagrangean relaxation and several heuristics. Dynamic column generation means that the duties are not generated a priori, but 'on the fly' during the solution process. The application of this dynamic approach is required by the fact that the complete set of feasible duties is extremely large in general, hence enumerating all feasible duties a priori is not feasible.

The overall execution is organized in a sequence of passes, in each of which the system tries to obtain better and better solutions. Within each pass, the algorithm iterates between the duty generation module and the duty selection module. The duty generation module generates new prospective feasible duties based on a number of dynamic programming heuristics. As customary, the effectiveness of a feasible duty is evaluated based on dual information related to the Linear Programming relaxation of the underlying model. However, TURNI uses Lagrangean relaxation and subgradient optimization instead of Linear Programming for calculating the required dual information. Feasible duties generated in earlier stages, whose effectiveness turns out to be low during later stages of the algorithm, may be deleted in order to keep the number of active duties manageable. The duty selection module heuristically looks for a solution for the overall model, based on the currently available set of feasible duties. The applied heuristic is also driven by the Lagrangean dual information. That is, the heuristic evaluates and selects duties from the set of active duties based on the Lagrangean dual information. Further details can be found in [4].

Within each pass, the generation and selection modules are applied cyclically for a certain number of iterations, thereby hopefully updating the best solution found. Thereafter a fixing procedure is activated to select some duties that appear to be particularly efficient and to fix them as belonging to the final solution. The overall process is then repeated on the trips not covered by the fixed duties: the duty generation and selection phases are iterated for a while on the subproblem resulting from fixing, new duties are fixed, etc. In this way, typically several millions of potential duties are evaluated within the duty generation module, and thousands of alternative solutions are constructed and evaluated during the selection phase. A heuristic refinement procedure is also applied from time to time, so as to hopefully improve the best solution by means of local trip exchanges among duties.

5.3 Computational results

Figures 2 and 3 show the results of a real-life case involving 14,678 trips related to all the work for the train drivers on a typical Tuesday. In Figure 2 we plot the number of duties in the current best solution (Heu. Sol.) and the current number of fixed duties (Fixed duties), whereas in Figure 3 we plot the Lagrangian lower bound available after each column generation. This value goes down quickly at the very beginning of the computation, when better and better duties are generated, and stabilizes after about 45 minutes. In the two figures only the first pass is considered. This pass took 4:06 hours on a PC Pentium 4 with 512 Mbyte RAM and a clock speed of 3.0 GHz, and ended up with an almost-optimal solution with 971 duties. The finally best solution delivered by TURNI had 965 duties (only 0.6% less), and was found in pass number 3, after 14:47 hours of computation. The cost of this solution was slightly refined in subsequent passes. The results represented in the figures are typical for the runs of TURNI on instances of comparable size.

6 Efficiency improvement

After its introduction within NS Reizigers in 2000, TURNI was used in several projects to study the effects of different sets of rules to be applied in the crew scheduling process. The system was also used in a bidding process, which finally resulted in the fact that NS Reizigers won a concession to operate trains in the

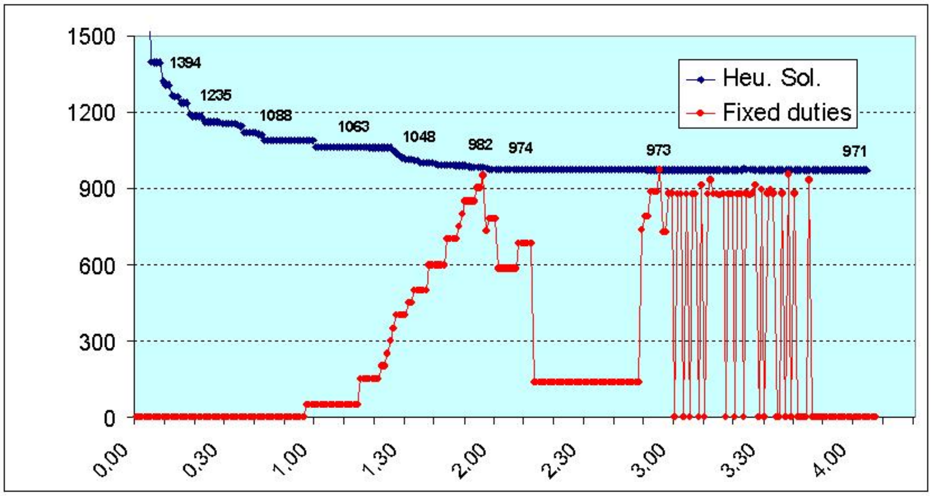

Figure 2: The number of duties (Heu. Sol.) in the incumbent solution and the number of fixed duties (Fixed duties) over CPU time

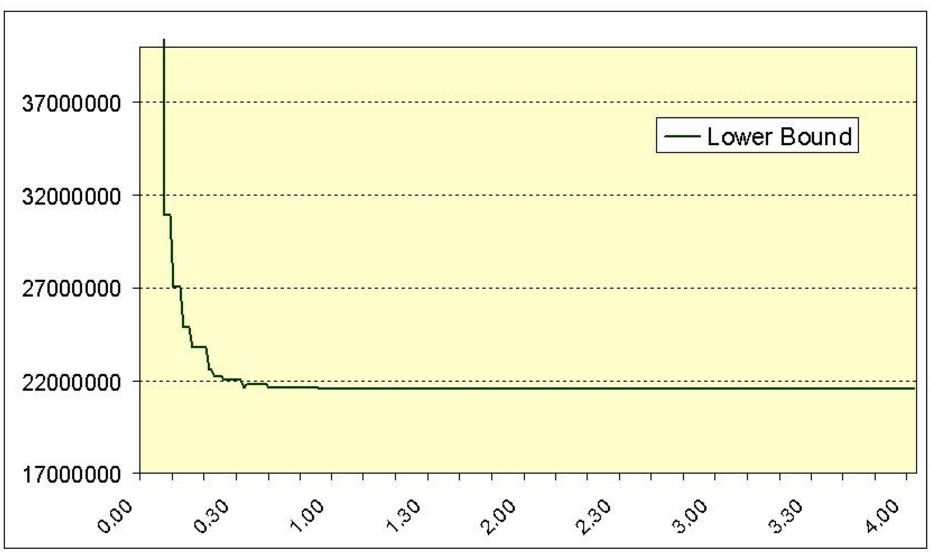

Figure 3: Lagrangean lower bound on the optimal solution cost over CPU time

neighborhood of Liverpool (United Kingdom) for many years.

Furthermore, NS Reizigers was considered to operate its trains quite efficiently already. Nevertheless, it is estimated that the realized savings by the use of TURNI can reach up to 2% per year. Indeed, the alternative production model was used in the construction of the duties for the drivers and conductors for the 2004 timetable. For this timetable, the total amount of work increased by about 3.2% in comparison with the 2003 timetable. This was the result of a higher number of trains for providing a better service to the passengers. However, together with TURNI, the planners succeeded to generate a set of duties that satisfied all the new rules, but that required only 1.2% more duties than in 2003. In other words, initial savings of about 2% were realized. On a total number of 6,500+ employees, this amounts to savings of over $7 million per year. In practice, the savings are estimated to be $4.8 million per year, since part of the initial savings were given away by the management in order to further increase the acceptance of the crew schedules by the drivers and the conductors. The final savings of 1.2% were still well above the target that was initially set by the management at 1%. These estimates of the savings are quite conservative, in particular because the generation of the crew schedules would simply have been impossible without the application of TURNI, as was said earlier.

The target for the crew schedules for 2005 is a further reduction in costs of about 3.5% per year. This is to be accomplished by a further intrinsic reduction of about 1% (the initial results for 2004 demonstrated that this may be feasible indeed), together with a reduction of about 2.5%, to be realized by relaxation of some of the constraints. For example, punctuality analyses have shown that a reduction of the transfer time for changing from one train to another from 25 minutes to 20 minutes will have only a minor negative effect on the punctuality, but will have a positive effect on the efficiency of the crew schedules.

7 Conclusions

At the start of this project, the working relations between the involved parties at NS Reizigers were that strained that nobody believed in the existence of a solution for the conflicts. However, a well directed combination of a participative approach for building up a solid basis and involvement of the personnel, together with expertise in Operations Research for the quantitative support, led to the required success. Operations Research revealed its power by facilitating the analysis of the complex scenarios. Moreover, in emotional discussions, quantitative results could be used as an independent judge to evaluate the arguments in an objective way. These objective and quantitative results also enabled the management of NS Reizigers to accept the alternative model.

The experiences with the alternative production model are quite positive so far. After the required extension of the route knowledge of the drivers had taken place, the introduction of the alternative production model on December 15, 2002, took place smoothly. Since then the average punctuality increased gradually from about 80% to about 85%[2]. Of course, the latter is not only due to the alternative production model, since also several other developments had a positive effect on the punctuality. Examples of such developments are the introduction of new, more dependable, rolling stock, and the intensified maintenance of the railway infrastructure by the Dutch government.

The only negative comments about the alternative production model come from the traffic control organization. Due to the more complex structure of the duties of the drivers and conductors, in real-time reconstructing the duties in case of a severe disruption of the train services is more difficult than in the time of the 'Church Circles'. However, these negative comments seem to be outweighed by the fact that the alternative production model has improved the motivation of the train drivers and conductors. The latter certainly has a positive effect on the punctuality of the railway services.

To the best of our knowledge, this is the first time that a large European railway company used Operations Research techniques successfully to actively support its crew scheduling process. Until recently, the sizes and complexities of the instances resulting from railway crew scheduling problems prohibited the successful application of such techniques. However, the application of TURNI supported NS Reizigers in developing the alternative production model to be

[2]An arriving train is considered to be 'on time' if it has a delay of 3 minutes or less.

applied in the crew scheduling process which shows a better balance between the relevant objectives. At the same time, the application of TURNI led to operational savings of about \$4.8 million per year. The application of TURNI has shown that savings of over \$30 million are achievable over the next 5 years.

A further recognized advantage of the use of a computerized planning support system is the fact that the organization becomes less dependent on the experience and the craftsmanship of the planners, Moreover, the application of such a system may facilitate a reduction of the throughput time of the logistic planning processes. The latter is important, since it implies an increased flexibility of the organization: a shorter throughput time of the planning processes allows the organization to react faster to changes in the environment.

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